

Chapter 5

Weather Influence on Solar Thermal Power Plants Operation on Mars

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5.1 Introduction

For many years space researchers realized that in some specific situations solar dynamic power systems can provide significant savings in life cycle costs when compared with conventional photovoltaic power systems with battery storage (Menetrey 1963; Secunde et al. 1989; Prisnjakov 1991; Prisnjakov et al. 1991). A standard solar dynamic power system uses a mirror to concentrate solar radiation onto an absorber structure. By conduction through a solid material or circulation of a working fluid, the absorber heat is transferred to a thermal engine (i.e. a turbogenerator, Stirling engine, termocouple or thermionic-emitter). Alternators coupled to these thermal engines may generate electrical energy. Previous practice proved that three different cycles can be used for thermodynamic conversion of solar radiation: Brayton, Rankine and Stirling (Menetrey 1963; Prisnjakov 1991; Prisnjakov et al. 1991). For continuous operation during dark periods the use of melted materials to store thermal energy is being considered. Among the advantages of dynamic power systems one could quote their ability to provide electrical energy and heat simultaneously, the fact that the power plant may be unified by using either solar or nuclear energy or their relative invulnerability to corpuscular particles and to electromagnetic radiation and the possibility of power control according to a given power consumption schedule (Prisnjakov 1991).

Earlier studies reported solar dynamic systems based on thermodynamic cycles and thermionic converters, respectively. Two systems of the former type were described in Menetrey (1963). One of them is a 3 kW solar dynamic system of 10 % overall efficiency consisting of a parabolic concentrator and a turbo-generator unit which uses mercury as working fluid in a Rankine cycle. The other one is a 15 kW system for space vehicle applications. Its working fluid is rubidium while the overall electrical efficiency is 21.7 %. The solar - thermionic system was designed to provide 135 W at Mars distance from the Sun with a system weighting about 14 kg. Other studies are using permanent gases (mainly mixtures of xenon and helium) as working fluid in Brayton cycles. They have output power of 3 to 5 kW, specific weights up to 40-45 kg/kW and overall efficiency of 31.2 % (Prisnjakov 1991; Prisnjakov et al. 1991, 1994). Significant efforts to develop solar dynamic power systems (25 kW) for application to a low Earth orbit space station have been conducted by NASA Lewis Research Center (LeRC) as an integral part of

the US space station development program (McLallian et al. 1988). The culmination of the LeRC programme demonstration program was a full system test in a thermal/vacuum tank of a Space Station Freedom type solar dynamic system at the 2 kWe size in February 1995. Related reports can be found in Secunde et al. (1989) and Weingartner et al. (1994). A comparison between the various power systems designed for the Space Station Freedom shows the sun-to-user efficiency is 5.7 to 6.8 % for the PV system and 18.7 to 19.8 % for the dynamic system. If, in addition, the storage subsystem is taken into consideration, the solar dynamic system becomes even more attractive, mainly because the efficiency of the latent heat storage is higher compared to the Ni-Cd batteries of the PV system (for details see Weingartner et al. (1994)).

A natural question arising about power systems to be used on Mars surface is: are properly designed dynamic systems comparable in performance with the PV – based power systems? Some of the above references seem to indicate an affirmative answer. However, they all refer to systems operating in the interplanetary space. A solar power system placed on Mars surface has to take into consideration one very important feature of the Martian weather. The period between the areocentric longitude $L_s=161 - 326^\circ$ and variants thereof have been referred to as the “dust storm season”. This period is nearly centered on perihelion, which is the time of maximum insolation on Mars (Martin and Zurek 1993; Hourdin et al. 1995). In the Northern hemisphere, the Martian atmosphere varies greatly from year to year during the dust storm season while during the other seasons, most phenomena are remarkably similar from year to year. A comprehensive description of Martian meteorology is provided by Zurek et al. (1992). Chapter 2 gives some information on the subject. The dust storm periods are characterized by an almost vanishing direct solar radiation (see e.g. Badescu (1998a) and Chap. 2). The main consequence is that isotropic diffuse solar radiation can not be concentrated and flat plate solar collectors have to be used in this case.

The structure of this chapter is as follows. Upper bounds for the efficiency of solar thermal power plants operating in the Martian environment are evaluated in section 5.2. A model of a solar power plant based on a Carnot cycle is presented in section 5.3 while section 5.4 refers to solar Stirling engines based on selective flat-plate converters. These models provide lower upper limits for the performance of actual thermal solar engines. Section 5.5 contains the conclusions.

5.2 Upper Limits for Solar Energy Conversion Efficiency into Work

The purpose of this section is to give information about the upper limits of the maximum efficiency of converting solar energy into mechanical work on the surface of Mars. This subject was already treated in a number of papers in case of solar energy conversion systems placed on Earth surface. Changing the conversion system on Mars does not require a different theoretical framework. However, the characteristics of Mars meteorology is expected to have considerable influence on the numerical results.

The upper bounds for the performance presented in this section are obtained by using highly idealized models. They have however the advantage of giving a perspective for the results obtained with the more realistic models developed in the next sections.

5.2.1 Exergy of Solar Radiation on Mars

The exergy of thermal radiation was studied in many papers, starting with the seminal work of (Petela 1964). Controversial arguments were presented in literature (see e.g. Bejan (1988) for an early review). More recently, the discussion was re-opened in relation with the exergy of solar radiation (Petela 2003; Candau 2003). Also, many authors studied the thermodynamics of converting radiation energy into mechanical work (for early reviews see Landsberg and Tonge (1979), Bejan (1988). Three different theories were proposed by Jeter (1981), by Landsberg, Petela and Press (Petela 1961; Landsberg and Mallison 1976; Press 1976) and by Spanner (1964), respectively. The three theories were unified in Bejan (1987) while a generalization was given in Badescu (1988). The exergy factor proposed by Landsberg-Petela-Press, which is very often used in literature, is:

$$\eta_{LPP} = 1 - \frac{4}{3} \frac{T_0}{T_s} + \frac{1}{3} \left(\frac{T_0}{T_s} \right)^4. \quad (5.1)$$

where T_0 and T_s are the ambient and Sun temperatures, respectively.

This factor shows the fraction of thermal radiation energy that can be converted into work. Note that η_{LPP} depends on just two temperatures (namely the temperatures of the two heat reservoirs).

Let us apply the above result in case of solar radiation on Mars. The temperature of solar direct radiation is $T_s=5760$ K while the average temperature of Mars surface is $T_0=248$ K. Equation (5.1) allows to compute the value of the Landsberg-Petela-Press exergy factor: $\eta_{LPP} = 0.9246$. For a solar direct irradiance at ground level $\phi_s=400$ W/m², the exergy flux is 377.04 W/m².

5.2.2 Accurate Upper Bounds for Solar Energy Conversion Efficiency

The theories shortly reviewed in the previous subsection predict efficiencies of converting radiation energy into work too high to be of practical interest. Much more accurate rigorous upper bounds for the real solar energy conversion efficiency η were reported in recent years (Badescu 1998b, 1998c). Some of these new results are listed below and applied to the special case of solar energy conversion on Mars surface.

(i) In case of a smaller than hemispherical blackbody radiation source and a blackbody receiver coupled to a reversible engine the upper bound of η is (Badescu 1998b):

$$\eta_i = 1 - \frac{4}{3} \left(f \frac{T_0}{T_s} \right) + \frac{1}{3} \left(f \frac{T_0}{T_s} \right)^4 > \eta, \quad (5.2)$$

where the geometric factor

$$f \equiv \left(\frac{\Omega}{\pi} \right)^{-1/4} \left(1 - \frac{\Omega}{4\pi} \right)^{-1/4} \quad (5.3)$$

is a function of the solid angle Ω subtended by the radiation source. In case of a spherical source of radiation (e.g. the Sun) the following simple relation applies:

$$f = \sin^{-1/2} \delta \quad (5.4)$$

where δ is the half-angle of the cone subtended by the source. Of course, when a hemispherical source of radiation is considered, $\delta = \pi/2$ and η_i given by Eq. (5.2) reduces to η_{LPP} given by Eq. (5.1). However, generally $\eta_i < \eta_{LPP}$. One can see that η_i depends on just two temperatures (namely the temperatures of the two heat reservoirs) in a way similar to the Carnot efficiency. But it also takes account of the geometry of the radiation source and this additional information increases its accuracy.

Let us apply Eqs. (5.2)-(5.4) to solar energy conversion on Mars. The case of direct solar radiation is considered. Then, δ is the half-angle of the cone subtended by the Sun when viewed from Mars. The mean distance Sun to Mars is $d_{Sun-Mars} = 227.94 \cdot 10^6$ km while Sun radius is $R_s = 696 \cdot 10^3$ km. Consequently, $\delta = \tan^{-1}(R_s/d_{Sun-Mars}) \approx \sin^{-1}(R_s/d_{Sun-Mars}) = 0.003053$. Equation (5.4) yields $f = 18.096$. Use of Eq. (5.2) gives the upper bound $\eta_i = 0.08393$. This is obviously a *more accurate* upper bound than those predicted in section 5.2.1.

(ii) In case of smaller than hemispherical blackbody radiation source and a blackbody receiver coupled to a Chambadal-Novikov-Curzon-Ahlborn (CNCA) engine the upper bound of η is (Badescu 1998b)

$$\eta_{ii} = 1 - \frac{4}{3} \left(f \frac{T_0}{T_s} \right)^{1/2} + \frac{1}{3} \left(f \frac{T_0}{T_s} \right)^2 > \eta. \quad (5.5)$$

This is of course a more accurate estimate for η than η_i is, because part of the entropy generation related to heat engine operation is taken into account. As an application, using Eq. (5.5) in case of solar direct radiation on Mars yields $\eta_{ii} = 0.02542$ which is lower than the value derived previously for η_i , as expected.

Note that a formula corresponding to η_{LPP} , in case the system contains a CNCA engine, can be obtained from Eq. (5.5) by making $f = 1$. One finds

$$\eta'_{ii} \equiv 1 - \frac{4}{3} \left(\frac{T_0}{T_s} \right)^{1/2} + \frac{1}{3} \left(\frac{T_0}{T_s} \right)^2. \quad (5.6)$$

Equation (5.6) provides a more accurate estimate for η than η_{LPP} , but a less accurate estimate than η_{ii} . Using Eq. (5.6) in case of solar direct radiation on Mars yields $\eta'_{ii} = 0.72395$. This is a rather high upper bound for the real efficiency and this loss in accuracy is the cost of using a simpler upper limit formula.

(iii) Repeating the procedure from Bejan (1987) but including details about some irreversibilities one finds relationships generalizing Jeter, Spanner and Landsberg-Petela-Press efficiencies, respectively (Badescu 1999). For example, the relation generalizing the last efficiency is:

$$\eta_{iii} \equiv 1 - \frac{4}{4-n} \left(\frac{T_0}{T_s} \right)^n + \frac{n}{4-n} \left(\frac{T_0}{T_s} \right)^4, \quad (5.7)$$

where n is a parameter related to the type of thermal engine. In case of $n = 1$ (i.e. a Carnot engine) one finds of course from Eq. (5.7) the efficiency η_{LPP} . Let us consider a CNCA engine ($n = 1/2$) as part of a power system converting the energy of direct solar energy on Mars. Then Eq. (5.7) yields the upper limit $\eta_{iii} = 0.76286$. This rather high upper bound is comparable in size to η'_{ii} .

(iv) The case of gray thermal radiation is of special interest, as it is sometimes used as an approximation for diffuse solar radiation. Note that gray radiation is a particular case of diluted radiation. A general theory was first developed by Landsberg and co-workers (see for instance the review paper by Landsberg and Tonge (1979)). However, important results were derived more recently and they will be summarized now. An accurate upper bound for the conversion efficiency of solar diluted radiation into work is given by Badescu (1990)

$$\eta_d \equiv 1 - \frac{4}{3} \left(f_d \frac{T_0}{T_s} \right) + \frac{1}{3} \left(f_d \frac{T_0}{T_s} \right)^4. \quad (5.8)$$

Here the dimensionless factor f_d can be obtained from Eqs. (10) and (14) of Badescu (1990):

$$f_d \equiv \chi(\varepsilon_d) \left(\frac{\Omega_d}{\pi} \right)^{-1/4} \left(1 - \frac{\Omega_d}{4\pi} \right)^{-1/4}, \quad (5.9)$$

where Ω_d is the solid angle subtended by the source of diluted radiation source while $\chi(\varepsilon_d)$ is a function of the radiation dilution factor ε_d . This function was calculated in Landsberg and Tonge (1979). It is such that $\chi(1)=1$ and can be approximated for small ε_d by:

$$\chi(\varepsilon_d) = 0.9652 - 0.2777 \ln \varepsilon_d + 0.0511 \varepsilon_d. \quad (5.10)$$

The above general formulation yields elegant results in the particular case of solar scattered radiation. The upper bound for the efficiency of converting into

work the energy of multiply scattered solar radiation was derived in Badescu (1991) and is given by

$$\eta_{d,i} \equiv 1 - \frac{4}{3} \left(f_{d,i} \frac{T_0}{T_s} \right) + \frac{1}{3} \left(f_{d,i} \frac{T_0}{T_s} \right)^4, \quad (5.11)$$

where the factor $f_{d,i}$ depends on the number i of scatterings ($i=1,2,3,4$). It is computed by

$$f_{d,i} \equiv \left(\frac{\Omega_{d,i}}{\pi} \right)^{-1/4} \left(1 - \frac{\Omega_{d,i}}{4\pi} \right)^{-1/4} \prod_{j=1}^i \chi(\varepsilon_{d,i}) \quad (i=1,2,3,4). \quad (5.12)$$

In case the scattered radiation is not subsequently concentrated, the following relations apply for the dilution factors and solid angles of i -scattered solar radiation, respectively:

$$\begin{aligned} \varepsilon_{d,1} &= \frac{\Omega_s}{\pi} & \varepsilon_{d,i} &= \frac{\Omega_s}{\pi} \left[\prod_{j=1}^{i-1} \chi^4(\varepsilon_j) \right] \quad (i=2,3,4) \\ \Omega_{d,i} &= 2\pi \left\{ 1 - \left[1 - \frac{\Omega_s}{\pi} \prod_{j=1}^i \chi^4(\varepsilon_{d,i}) \right]^{\frac{1}{2}} \right\} \quad (i=1,2,3,4), \end{aligned} \quad (5.13,14)$$

where Ω_s is the solid angle subtended by the Sun. The half-angle $\delta_{d,i}$ of the cone subtended by the source of i -scattered radiation can be easily computed from:

$$\Omega_{d,i} = 2\pi(1 - \cos \delta_{d,i}). \quad (5.15)$$

The effective temperature $T_{d,i}$ of i -scattered solar radiation is given by:

$$T_{d,i} = \frac{T_s}{\prod_{j=1}^i \chi(\varepsilon_{d,i})}. \quad (5.16)$$

Table 5.1 shows results obtained in case of i -scattered solar radiation on Mars. One can see that after a single scattering (i.e. $i=1$) solar radiation is still strongly anisotropic (compare $\delta_{d,1} = 3.061^\circ$ with the half-angle $\delta_s = 0.1749^\circ$ of the cone subtended by the Sun). After four scatterings solar radiation is isotropic and an observer at the ground would see a uniformly brilliant sky. The effective temperature of the scattered radiation decreases by increasing the number of scatterings, as expected. However, the upper bound efficiency $\eta_{d,i}$ predicted by Eq. (5.11) yields the same value, whatever the number of scatterings. This is a consequence of keeping the energy flux constant during the scattering process.

Table 5.1 Upper bounds for the conversion efficiency of i -scattered solar radiation into work on Mars.

Number of scatterings, i	$\varepsilon_{d,i}$	$\Omega_{d,i}$	$\delta_{d,i}$ (deg)	$T_{d,i}$ (K)	$\eta_{d,i}$	$C_{\max,i}$	$\eta_{d,\text{conc},i}$
1	0.00000932	0.00897	3.06	1377.0	0.084	350.70	0.760
2	0.00285100	0.41880	21.04	531.2	0.084	7.76	0.393
3	0.12890000	2.99700	58.47	344.8	0.084	1.38	0.130
4	0.72650000	6.28300	90.00	316.0	0.084	1.00	0.084

$\varepsilon_{d,i}$ - dilution factor. $\Omega_{d,i}$ and $\delta_{d,i}$ - solid angle and half-angle of the cone subtending the source of radiation, respectively. $T_{d,i}$ - effective temperature. $\eta_{d,i}$ - upper bound efficiency. $C_{\max,i}$ - maximum concentration ratio. $\eta_{d,\text{conc},i}$ - upper bound efficiency for concentrated i -scattered radiation. Sun temperature $T_s=5760$ K; average temperature on Mars surface $T_0=248$ K.

For small i -values scattered solar radiation is generally anisotropic. Consequently, it can be concentrated. The maximum concentration ratio $C_{\max,i}$ is given by:

$$C_{\max,i} = \left[\frac{\Omega_{d,i}}{\pi} \left(1 - \frac{\Omega_{d,i}}{4\pi} \right) \right]^{-1}. \quad (5.17)$$

The upper bound efficiency $\eta_{d,\text{conc},i}$ for fully concentrated scattered radiation is given again by Eq. (5.11) with $f_{d,i}$ replaced by $f'_{d,i}$ given by:

$$f'_{d,i} \equiv \prod_{j=1}^i \chi(\varepsilon_{d,j}) \quad (i=1,2,3,4). \quad (5.18)$$

The upper bound efficiency $\eta_{d,\text{conc},i}$ lies between 0.760 and 0.084 for single and four scatterings, respectively (Table 5.1). Generally, the effective temperature of scattered radiation is lower, and the upper bound efficiency is higher, on Mars than on Earth (compare present Table 5.1 with Table 1 of Badescu (1991)). This is mainly caused by the lower ambient temperature on Mars.

(v) The upper bounds at (i) to (iii) above apply to any source of blackbody undiluted or diluted radiation. Even more accurate (but also more complex) upper bounds of η were derived in case of solar energy applications (Badescu 1998c, 2000). These upper bounds do not involve the absorber temperature but are expressed just in terms of the two heat reservoir temperatures. However, they take into account a large number of details concerning the conversion process as for example, the dilution factors of solar and ambient radiation, the polarization degree of solar and absorber emitted radiation and the thermal and optical properties of the selective absorber (convective and conductive heat loss coefficients, concentration ratio, effective transmittance-absorptance product and emittances). These details increase of course the accuracy of the efficiency formula. As an example we shall use the accurate upper bound efficiency Eq. (36) of Badescu (1998c). For the purposes of this chapter we shall simplify it to take account just

on the selective properties of the absorber (i.e. its absorptance a and emittance e). Then, the upper bound efficiency is given by:

$$\eta_v = a \left[1 - \frac{4}{3} \left(f \frac{T_0}{T_s} \right) + \frac{1}{3} \left(f \frac{T_0}{T_s} \right)^4 \right], \quad (5.19)$$

where

$$f = \left(\frac{e}{a} \right)^{1/4} \sin^{-1/2} \delta. \quad (5.20)$$

For an usual selective flat-plate solar collector with $a = 0.9$ and $e = 0.1$, Eq. (5.19) yields $\eta_v = 0.3724$ which is considerably higher than the upper bound efficiency $\eta_i = 0.08393$ we previously found in case of black-body (non-selective) solar collectors.

Finally, note that the results presented in (i), (ii) and (v) correspond to solar direct radiation at normal incidence (i.e. Sun zenith angle $\theta_0 = 0$). In the general case the geometric factors in Eqs. (5.3), (5.4) and (5.20) should be multiplied by $\cos^{-1/4} \theta_0$ (Landsberg and Badescu 2000). For oblique radiation incidence ($\theta_0 > 0$) this procedure will yield lower estimates for the upper bound efficiency.

5.3 Carnot Solar Power Plants with External Irreversibility

In Sect. 5.2 we presented simple accurate upper bound formulas for the efficiency of solar power plants operating on Mars. Much more involved models are necessary to further increase the accuracy of results. A solar power plant model based on the Carnot cycle with external irreversibility is presented here. This approach keeps the advantage of generality but also takes into account the irreversibilities associated to the heat transfer at the hot and cold components of the plant.

5.3.1 Solar Power Plant Model

Generally, a solar power plant consists of a solar collector, a thermal engine and a heat storage system. A solar collector mainly consists in mirror, absorber (receiver), transparent cover(s) and thermal insulation. The mirror is missing in case of flat - plate collectors while for some concentration systems the receiver is not protected by transparent cover(s). The solar power plant analysed in this section is designed to operate during the whole Martian year. Consequently, it consists of a flat-plate *selective* solar collector coupled to a thermal engine. No heat storage system is considered in this approach.

5.3.1.1 Solar Collector Model

A selective flat - plate solar collector is shown in Fig. 5.1. Its main components are: the absorber plate (1) with pipes for the working fluid and a transparent cover

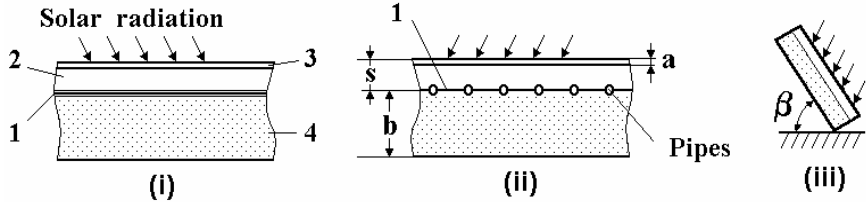


Fig. 5.1 Solar collector. (i) longitudinal section; (ii) transversal section; (iii) lateral view. 1 - absorber plat; 2 - carbon dioxide layer; 3 - transparent cover; 4 - bottom thermal insulation

(3) of thickness a . The gap between (1) and (3) (thickness s) is filled with carbon dioxide at the Martian atmospheric pressure (carbon dioxide represents 95 % of the Martian atmosphere). The bottom thermal insulation (4) has a thickness b . The collector tilt angle is β . One denotes by T_C and T_a the absorber plate and ambient temperatures, respectively. Other temperatures related to collector operation are defined in Table 5.2.

Table 5.2 Various temperatures related to solar collector operation

T_C	absorber plate temperature
T_{si}	temperature of lower surface of transparent cover
T_{ss}	temperature of higher surface of transparent cover
T_a	atmosphere temperature
$T_{C,si} = (T_C + T_{si})/2$	average fluid temperature between absorber plate and lower surface of transparent cover (see Fig. 5.2)
$T_{s,ave} = (T_{si} + T_{ss})/2$	average transparent cover temperature
$T_{ss,a} = (T_{ss} + T_a)/2$	average temperature of the atmosphere boundary layer near the collector transparent cover
$T_{iz} = (T_C + T_a)/2$	average bottom insulation temperature

Direct beam (b), diffuse (d) and ground reflected (r) fluxes of solar energy are incident on the collector. Their magnitude depends upon collector's tilt and orientation. Generally, the incident and absorbed solar energy density fluxes (φ_{inc} and φ_{abs} , respectively) are given by

$$\begin{aligned}\varphi_{inc} &= G_b + G_d + G_r \\ \varphi_{abs} &= (\tau\alpha)_b G_b + (\tau\alpha)_d (G_d + G_r).\end{aligned}\quad (5.21,22)$$

Here G 's denote solar irradiances at collector level while $(\tau\alpha)$'s are effective transmittance - absorptance products.

The collector heat losses are studied by using the thermal resistance method (Eaton and Blum 1975) (see Fig. 5.2 and Table 5.3). Then, the flux of heat losses from the collector towards the ambient is given by:

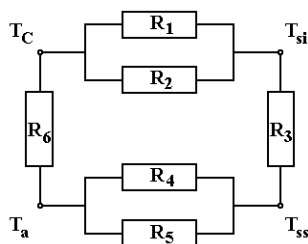


Fig. 5.2 Solar collector thermal resistances. T_a - ambient temperature; T_c - absorber plate temperature; T_{si} - temperature of lower surface of transparent cover; T_{ss} - temperature of upper surface of transparent cover

Table 5.3 Thermal resistances associated to solar collector operation (see Figs. 5.1 and 5.2)

Thermal Resistance	Process
R_1	Convection and conduction between absorber plate (1) and transparent cover (3)
R_2	Radiation between absorber plate (1) and the lower surface of the transparent cover (3)
R_3	Conduction through transparent cover (3)
R_4	Radiation between the higher transparent cover surface (3) and Martian atmosphere
R_5	Convection between the higher transparent cover surface (3) and Martian atmosphere
R_6	Conduction through the bottom thermal insulation(4)

$$q_{tot} = U_L (T_c - T_a) = (T_c - T_a) / R_{tot}, \quad (5.23)$$

where U_L is the overall heat losses coefficient while R_{tot} is the total thermal resistance. U_L is given by (see Fig. 5.2):

$$U_L = \frac{1}{R_{tot}} = \frac{1}{R_{1-5}} + \frac{1}{R_6}, \quad (5.24)$$

where the equivalent resistance R_{1-5} is computed from:

$$R_{1-5} = \frac{R_1 R_2}{R_1 + R_2} + R_3 + \frac{R_4 R_5}{R_4 + R_5}. \quad (5.25)$$

Details concerning the evaluation of thermal resistances follow. The thermal resistance R_1 is computed from

$$R_1 = \frac{s}{< \lambda_{CO_2} > Nu_{C,si}}, \quad (5.26)$$

Table 5.4 (a) Relationships for convection heat transfer between absorber plate and transparent cover (Eaton and Blum 1975); **(b)** General relationships for convection heat transfer between two plane parallel surfaces (Stefanescu et al. 1982, p. 160)

(a) $Nu_{C,si} = \left(1 - \frac{\beta}{2\pi}\right)Nu_H + \frac{\beta}{2\pi}Nu_V$	
$Nu_H = 0.195 \cdot Gr^{0.25}$	for $2 \cdot 10^3 \leq Gr < 4 \cdot 10^5$
$Nu_H = 0.068 \cdot Gr^{0.33}$	for $Gr \geq 4 \cdot 10^5$
$Nu_V = 0.180 Gr^{0.25} (s/L)^{0.11}$	for $1 \cdot 10^4 \leq Gr < 2 \cdot 10^5$
$Nu_V = 0.065 Gr^{0.33} (s/L)^{0.11}$	for $2 \cdot 10^5 \leq Gr < 11 \cdot 10^6$
(b) $Nu_{C,si} = 1$	
$Nu_{C,si} = 0.105 \cdot (Gr \cdot Pr)^{0.30}$	for $1 \cdot 10^3 < Gr \cdot Pr \leq 1 \cdot 10^6$
$Nu_{C,si} = 0.400 \cdot (Gr \cdot Pr)^{0.20}$	for $1 \cdot 10^4 \leq Gr < 2 \cdot 10^5$
$Nu_{C,si} = 0.180 \cdot (Gr \cdot Pr)^{0.25}$	for $Gr \cdot Pr > 1 \cdot 10^{10}$

H and V denote a horizontal and vertical solar collector; β [rad] and L are tilt angle and collector length, respectively.

where $\langle \lambda_{CO_2} \rangle_{C,si}$ is thermal conductivity of carbon dioxide and $Nu_{C,si}$ is Nusselt number, both of them evaluated at the average fluid temperature $T_{C,si}$.

To compute $Nu_{C,si}$, a number of criterial relationships developed for solar collectors are used (Table 5.4a) (Eaton and Blum 1975). For cases not covered by Table 5.4a we use the general relationships from Stefanescu et al. (1982) (Table 5.4b). Prandtl and Grashoff numbers in Table 5.4 were computed with:

$$Pr = \frac{\langle c_{p,CO_2} \rangle_{C,si} \langle \eta_{CO_2} \rangle_{C,si}}{\langle \lambda_{CO_2} \rangle_{C,si}}, \quad Gr = \frac{g_M p_{CO_2}^2 s^3 (T_C - T_{si})}{\langle \eta_{CO_2} \rangle_{C,si} R_{CO_2} T_{C,si}} \quad (5.27)$$

where g_M is gravitational acceleration on Mars while p_{CO_2} and R_{CO_2} are the pressure and gas constant for the carbon dioxide between absorber plate and transparent cover. In Eq. (5.27) the specific heat at constant pressure ($\langle c_{p,CO_2} \rangle_{C,si}$), the dynamic viscosity ($\langle \eta_{CO_2} \rangle_{C,si}$) and the thermal conductivity ($\langle \lambda_{CO_2} \rangle_{C,si}$) of carbon dioxide were interpolated at the average temperature $T_{C,si}$. In computations the thermal properties of carbon dioxide from Pop et al. (1987) were used.

The thermal resistance R_3 is given by:

$$R_3 = a / \lambda_s. \quad (5.29)$$

The temperature dependence of transparent cover's thermal conductivity (λ_s) was described by using an interpolation parabolic function whose coefficients were obtained by using experimental data (the transparent cover is made of crystal; thermal

properties are found in Lide (1991)). The average transparent cover temperature $T_{s,ave}$ is used in computations.

The thermal resistance R_4 is evaluated with:

$$R_4 = \frac{1/\varepsilon_2}{2\sigma(T_{ss}^2 + T_a^2)T_{ss,a}}, \quad (5.30)$$

where $T_{ss,a}$ is the average temperature of the atmosphere boundary layer near the collector transparent cover.

Because of the wind, the heat transfer between the transparent cover and Martian atmosphere is mainly by forced convection. Thus, the thermal resistance R_5 was computed from:

$$R_5 = \frac{L}{<\lambda_{CO_2}>_{ss,a} N u_{ss,a}}, \quad (5.31)$$

where L is collector's length on wind direction and $<\lambda_{CO_2}>_{ss,a}$ is carbon dioxide thermal conductivity at temperature $T_{ss,a}$. In Eq. (5.31) $Nu_{ss,a}$ depends on the critical length X_T which separates the laminar and turbulent wind flows over the collector. The relationships of Table 5.5 are used. The Reynolds and Prandtl numbers are evaluated with:

$$Re = \frac{p_{CO_2} W L}{<\eta_{CO_2}>_{ss,a} R_{CO_2} T_{ss,a}}, \quad Pr = \frac{<c_{p,CO_2}>_{ss,a} <\eta_{CO_2}>_{ss,a}}{<\lambda_{CO_2}>_{ss,a}}, \quad (5.32)$$

where W is wind speed and the thermal properties of the atmosphere ($<\eta_{CO_2}>_{ss,a}$, $<c_{p,CO_2}>_{ss,a}$ and $<\lambda_{CO_2}>_{ss,a}$) are interpolated at the average temperature $T_{ss,a}$.

The thermal resistance R_6 is evaluated with:

$$R_6 = b/\lambda_{iz} \quad (5.33)$$

where λ_{iz} is bottom insulation thermal conductivity, computed at the average temperature T_{iz} .

Table 5.5 Relationships for forced convection heat transfer between transparent cover and atmosphere (Stefanescu et al. 1982, p. 126)

$X_T = 5 \cdot 10^5 \frac{<\eta_{CO_2}>_{ss,a} R_{CO_2} T_{ss,a}}{p_{CO_2} W}$	
$Nu_{ss,a} = 0.335 \cdot Re^{0.50} \cdot Pr^{0.50}$	for $L \leq X_T$ (laminar flow)
$Nu_{ss,a} = 0.036 \cdot Re^{0.80} \cdot Pr^{0.75}$	for $L > X_T$ (turbulent flow)

5.3.1.2 Engine Model

A variety of working fluids were proposed to be used in space solar engines. They include mercury, potassium and rubidium in the early studies (Menetrey 1963) or organic fluids and mixtures of noble gases more recently (Prisnjakov et al. 1991; Angelino and Invernizzi 1993). The later seem to be more appropriate in case of Martian solar power plants. The largest and smallest working fluid temperatures are denoted T' and T'' , respectively (Fig. 5.3).

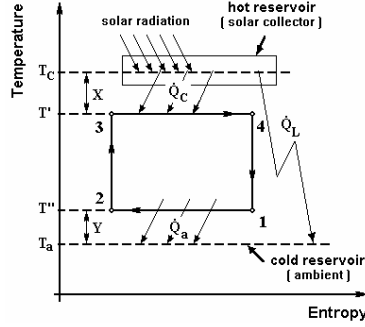


Fig. 5.3 Temperature - entropy diagram for a Carnot cycle with external irreversibility (for notations see text)

Generally, $T_C > T'$ and $T'' > T_a$. Hence, both

$$X \equiv T_C - T' \text{ and } Y \equiv T'' - T_a \quad (5.34)$$

are positive quantities. The flux of solar energy ϕ_{abs} absorbed by the collector is

$$\phi_{abs} = \phi_{abs} A_C, \quad (5.35)$$

where A_C is collector surface area. Part of this flux is transferred to the working fluid ($\dot{Q}_C$) while the other part constitutes the flux of thermal losses to the ambient ($\dot{Q}_L$). Then, the solar collector steady-state energy balance is:

$$\phi_{abs} - \dot{Q}_C - \dot{Q}_L = 0. \quad (5.36)$$

The heat fluxes $\dot{Q}_C$ and $\dot{Q}_L$ can be written as:

$$\dot{Q}_C = h_C A_C X \text{ and } \dot{Q}_L = U_L A_C (T_C - T_a), \quad (5.37)$$

where h_C and U_L are appropriately defined overall heat transfer coefficients between the solar collector and the working fluid and ambient, respectively.

The Carnot engine partially converts the flux $\dot{Q}_C$ into power. Thus:

$$\dot{Q}_C = \dot{W} + \dot{Q}_a, \quad (5.38)$$

where $\dot{W}$ is the output power and $\dot{Q}_a$ is the thermal energy flux finally reaching the surroundings. There is no further increase of entropy during work production. Consequently

$$\frac{\dot{Q}_C}{T'} + \frac{\dot{Q}_a}{T''} = 0. \quad (5.39)$$

The heat flux $\dot{Q}_a$ can be written as

$$\dot{Q}_a = h_a A_a Y, \quad (5.40)$$

where A_a and h_a are appropriately defined engine radiator heat transfer area and overall heat transfer coefficient between working fluid and ambient, respectively.

5.3.1.3 Performance Indicators

Four performance indicators may be considered in relation to Martian solar plant operation (Badescu et al. 1999, 2000a, 2000b). First, there is the Carnot engine efficiency defined as:

$$\eta_{engine} \equiv 1 - \frac{T''}{T'}. \quad (5.41)$$

Second, there is the output power $\dot{W}$, evaluated from:

$$\dot{W} = h_C A_C X - h_a A_a Y. \quad (5.42)$$

Here we used the Eqs. (5.37), (5.38) and (5.40). Third, there is the system efficiency, defined as:

$$\eta_{system} \equiv \frac{\dot{W}}{\phi_{abs} A_C}. \quad (5.43)$$

Finally, the solar (or sun-to-user) efficiency is defined as:

$$\eta_{solar} \equiv \frac{\dot{W}}{\phi_{abs} A_C}. \quad (5.44)$$

Information about some of these indicators is reported in the following. The exergetic efficiency has been not reported for reasons of space.

5.3.1.4 Optimisation

The output power $\dot{W}$ is maximised now. The weight of space power plants should be kept at minimum. Following previous studies (see e.g. Badescu (1994)) we express the mass of the total heat transfer area (i.e. the mass M_C of the solar collector and the mass M_a of the engine radiator) as a k fraction from the total mass M_{tot} of the space system:

$$M_C + M_a = kM_{tot} . \quad (5.45)$$

One denotes d_c and d_a the superficial mass density of collector and radiator, respectively. One can simply write:

$$M_C = d_C A_C , \quad M_a = d_a A_a . \quad (5.46)$$

One can use $d_C = d_a$ as a reasonable assumption. By using Eqs. (5.45) and (5.46) one derives the following constraint to be fulfilled:

$$A_C + A_a = A \equiv k \frac{M_{tot}}{d_a} . \quad (5.47)$$

Other constraints (say F_1 and F_2) are the Eqs. (5.36) and (5.39). By using Eqs. (5.34), (5.37) and (5.40) they become:

$$\begin{aligned} F_1 &\equiv \frac{h_C A_C X}{T_C - X} - \frac{h_a (A - A_C)}{T_a + Y} = 0 \\ F_2 &\equiv \varphi_{abs} - U_L (T_C - T_a) - h_C X = 0 \end{aligned} \quad (5.48,49)$$

The power $\dot{W}$ is considered here as a function of T_C , X , Y and A_C . The Lagrange function L associated to $\dot{W}$ is:

$$L \equiv \dot{W} + \lambda_1 F_1 + \lambda_2 F_2 , \quad (5.50)$$

where λ_1 and λ_2 are multipliers. The maximum output power is obtained by solving the six equations shown in Table 5.6.

Table 5.6 Equations to be solved for power maximisation (for details see text)

1.	$\frac{\partial L}{\partial T_C} = -\lambda_1 \frac{h_C A_C X}{(T_C - X)^2} - \lambda_2 U_L = 0$
2.	$\frac{\partial L}{\partial X} = h_C A_C + \lambda_1 \frac{h_C A_C T_C}{(T_C - X)^2} - \lambda_2 h_C = 0$
3.	$\frac{\partial L}{\partial Y} = -h_a (A - A_C) - \lambda_1 \frac{h_a (A - A_C) T_a}{(T_a + Y)^2} = 0$
4.	$\frac{\partial L}{\partial A_C} = h_C X + h_a Y + \lambda_1 \left(\frac{h_C X}{T_C - X} + \frac{h_a Y}{T_a - Y} \right) = 0$
5.	$\frac{\partial L}{\partial \lambda_1} = \frac{h_C A_C X}{T_C - X} - \frac{h_a (A - A_C) Y}{T_a + Y} = 0$
6.	$\frac{\partial L}{\partial \lambda_2} = \varphi_{abs} - U_L (T_C - T_a) - h_C X = 0$

Table 5.7 Optimum parameters for maximum output power (for details see text)

1.	$T_{C,opt} = \left(1 + f - \frac{1 + f - (1 + f)^{1/2}}{K^{1/2} (1 + K^{1/2})} \frac{h_a}{U_L} \right) T_a$
2.	$X_{opt} = \frac{(1 + f) - (1 + f)^{1/2}}{K^{1/2} (1 + K^{1/2})} \frac{h_a}{h_C} T_a$
3.	$Y_{opt} = \frac{(1 + f)^{1/2} - 1}{1 + K^{1/2}} T_a$
4.	$A_{C,opt} = \frac{K^{1/2}}{1 + K^{1/2}} A$

Table 5.7 shows the solution that applies for $K > 1$. There, the dimensionless parameters K and f are defined as:

$$K = \frac{h_a}{h_C} \left(1 + \frac{h_C}{U_L} \right), \quad f = \frac{\varphi_{abs}}{U_L T_a}. \quad (5.51)$$

Table 5.7 and Eq. (5.42) allow writing the maximum power as:

$$\dot{W}_{max} = \frac{h_a A}{T_a} Y_{opt}^2 \quad (5.52)$$

The optimum solar efficiency $\eta_{solar,opt}$ can be derived by using Eqs. (5.44), (5.52) and Table 5.7.

5.3.2 Results and Discussions

One of the goals of this chapter is to perform a rough comparison between the performance of PV cell power systems and dynamic solar power plants. In case of PV cell systems we had in mind the Pathfinder's Sojourner. Sojourner is a small (11.5 kg), six - wheel robotic vehicle built at Jet Propulsion Laboratories. Sojourner was landed on Mars aboard the Pathfinder spacecraft on July 4, 1997. In the same sol (i.e. Martian day) she began to traverse the Martian terrain, perform science and technology experiments, and transmit images and data back to the Lander spacecraft. Sojourner's equipment (computers, motors, radio modem) was mainly powered by a lightweight 0.34 kg solar array of receiving surface area 0.22 m². The PV cell system was designed to provide Sojourner with around 16 W of electric power at noon on Mars. The landing place was in Ares Vallis at 19.17° N and 33.21° W on the U.S. Geological Survey (USGS) cartographic network (Golombek et al. 1997). Pathfinder landed in late northern summer (areocentric longitude $L_s=143^\circ$) and operated for 83 sols.

To allow comparison with Sojourner performance an appropriately designed dynamic power plant equipped with a flat - plate selective solar collector is analyzed here (see Table 5.8). A number of assumptions are accepted as follows. A simple relation is used for the effective transmittance - absorptance products:

Table 5.8 Details about selective flat - plate solar collector design

Quantity	Notation	Value
Number of transparent covers	N	1
Transparent cover thickness	a	0.003 m
Distance between transparent cover and absorber plate	s	0.045 m
Bottom thermal insulation thickness	b	0.1 m
Short wavelengths transparent cover transmittance	τ_{cs}	0.82
Short wavelength transparent cover absorptance	α_{ps}	0.90
Long wavelengths (IR) absorber plate emittance	ε_1	0.10
Long wavelengths (IR) transparent cover emittance	ε_2	0.88
Thermal conductivity of bottom insulation (polyurethane)	λ_b	0.02 W/(mK)

($A_C = 0.22 \text{ m}^2$)

$$(\tau \alpha)_b = (\tau \alpha)_d = \tau_{cs} \alpha_{ps}, \quad (5.53)$$

where τ_{cs} and α_{ps} are the transparent cover transmittance and absorber absorptance, respectively, both of them for short (solar) wavelengths. The collector's transparent cover is made up of crystal (light flint glass). Its thermal conductivity lies between 0.691 W(mK)^{-1} at -100°C and 1.025 W(mK)^{-1} at $+100^\circ\text{C}$ (Lide 1991). The ratio $0.34/11.5=0.0296$ between the PV array weight and total Sojourner weight can be used as a first estimate for the coefficient k appearing in Eq. (5.47). Preliminary tests were performed to determine an optimum collector area $A_{C,opt}$ close to Sojourner PV cell surface area (0.22 m^2). Finally, the value $A=0.23 \text{ m}^2$ was used in computations. It corresponds to a radiator superficial mass density $d_a=1.48 \text{ kg/m}^2$ in Eq. (5.47). It is rather close to the value $d_a=2.3 \text{ kg/m}^2$ accepted in Angelo and Buden (1991) in case of the radiator of a nuclear power satellite but only half of the value $d_a=3 \text{ kg/m}^2$ accepted in Mozjorine et al. (1991) for a solar space power station.

The distance between VL1 and Pathfinder Lander is around 815 km. Thus, one expects quite similar meteorological and actinometric features in both places.

Four strategies of collecting solar energy were considered in preliminary tests (Badescu 1998a). The following two strategies will be used in this section: (i) horizontal collector - strategy H; (ii) the collector tilt and orientation are continuously adjusted to keep the receiving surface perpendicular on Sun's rays - strategy P. Strategy H is easier to use while strategy P gives the higher power output most time of the year.

5.3.2.1 Solar Collector Operation

Solar collector thermal losses mainly depend on the heat transfer regime between absorber plate and transparent cover (separated through the layer 2 of thickness s in Fig. 5.1). We considered the case of a horizontal solar collector. Three design

Table 5.9 Three design solutions for the system solar collector - thermal engine

Case	h_a [W/(m ² K)]	h_c [W/(m ² K)]	Thermal engine performance level
(a)	1	1	Low efficiency
(b)	10	10	Medium efficiency
(c)	500	50	High efficiency

h_a = heat transfer coefficient between the working fluid passing through the radiator of the heat engine and ambient (see Eq. (5.40)); h_c = heat transfer coefficient between solar collector and working fluid (see Eq. (5.37)).

solutions for the system solar collector - thermal engine were analysed (Table 5.9). They correspond to three different performance levels. For analysis we have chosen the middle of a clear sky autumn sol, when the thermal losses are rather high (sol 301 VL1, 14.04 local solar time (LST)). [We remind that sol numbering started when each Viking Lander touched down the Martian soil.]

The dependence of the overall heat loss coefficient U_L on the distance s between absorber plate and transparent cover is shown in Fig. 5.4 for the three cases of Table 5.9. The heat losses decrease by increasing s . This is specific to the conduction heat transfer regime. The thickness s is limited, however, by economic reasons. In the following we use s =0.045 m and the high efficiency engine (case (c) in Table 5.9). Note that the chosen value of s is about two times larger than the usual value for Earth placed solar collectors.

For Earth placed solar collectors the heat transfer between absorber plate and transparent cover is mainly by convection. This prompted various technical solutions meant to keep convection at local level (the honeycombs and Francia cells are examples of solutions for convection suppression) (see Meinel and Meinel

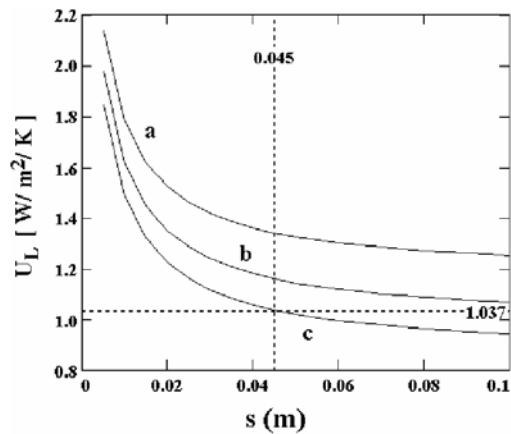


Fig. 5.4 Overall heat loss coefficient U_L as a function of parameter s (distance between absorber plate and transparent cover - see Fig. 5.1). Three design solutions (a), (b),(c) are considered (see Table 5.9). (VL1 site, autumn, sol 301, 14.04 LST)

(1976, p. 404)). The convective heat transfer is activated when the product $Gr \cdot Pr$ exceeds 1000 (see Table 5.4b). We analysed the heat transfer above the absorber plate by using the whole set of available meteorological data (Table 2.2 of Chap. 2). The results show that the product $Gr \cdot Pr$ varies between 9.65 and 211.2, well below the threshold value of 1000. We draw the important conclusion that on Mars the thermal losses between absorber plate and transparent cover are exclusively by conduction.

The convection heat losses from transparent cover to atmosphere are mainly controlled by wind speed. The change from laminar to turbulent convection occurs in case the heat transfer surface exceeds a certain critical length X_T (see Table 5.5). The flow regime above the transparent cover was analysed by using the whole set of available meteorological data. Results are shown in Fig. 5.5. The minimum value of the critical length X_T is 5.43 m. Consequently, the convection heat transfer above the transparent cover is laminar. The critical length X_T is smaller during winter and larger during summer (Badescu et al. 2000a). No significant difference between VL1 and VL2 sites is observed (note that a larger number of meteorological values are available for VL2 - see Table 2.2 of Chap. 2). The critical length obviously decreases when the optical depth increases. During the "clear sky" days ($\tau < 1$) the critical length values have an important dispersion. Scattering diminishes during the dust storm days ($\tau > 1$).

For the design solution we selected (case (c) in Table 5.9), the values of the overall heat loss coefficient U_L range between about 0.5 and 1 $\text{Wm}^{-2}\text{K}^{-1}$ (Fig. 5.6). Broadly, these values are comparable with those of Earth located vacuum solar

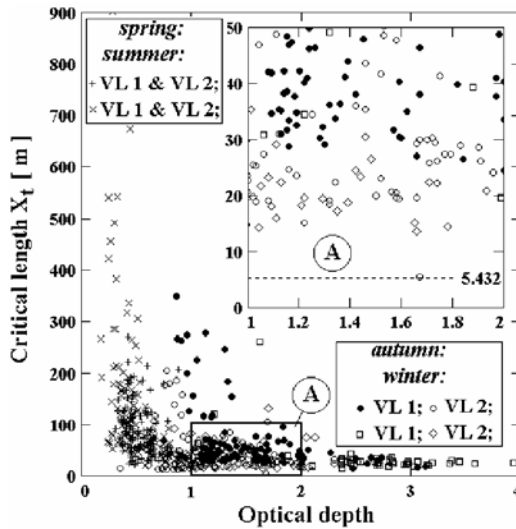


Fig. 5.5 Critical length X_T (see Table 5.5) as a function of optical depth. A high efficiency engine was considered (see Table 5.9). All the available meteorological data were used.

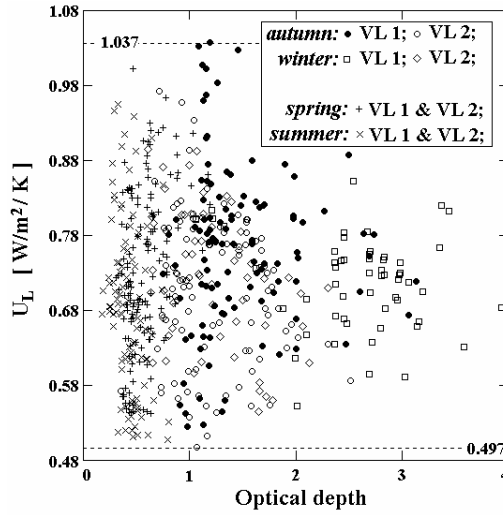


Fig. 5.6 Overall heat loss coefficient U_L as a function of optical depth. A high efficiency engine was considered (see Table 5.9). All the available meteorological data were used.

collectors (see e.g. Meinel and Meinel (1976, p. 387)). The dispersion of the U_L values is slightly smaller during winter and higher during autumn (Badescu et al. 2000a). No obvious dependence of U_L on the optical depth is observed. However, the dispersion of the U_L values is larger for values $\tau < 1$, i.e. during the "clear" days. Also, Fig. 5.6 shows that U_L does not depend significantly on the latitude of the solar collector.

5.3.2.2 Thermal Engine Operation

The parameters h_a and h_c have an important influence on performance. For analysis we have chosen the middle of a clear sky autumn day (sol 301 VL1, 14.04 LST). Some results are shown in Fig. 5.7 for the maximum power provided by the thermal engine. The influence of both h_a and h_c is more important on the maximum power provided by the heat engine than on the overall efficiency (Badescu et al. 2000a).

Generally, the influence on performance is strong for low values of both heat transfer coefficients h_a and h_c (less than $100 \text{ W m}^{-2} \text{ K}^{-1}$). The performances are practically not dependent on the higher values of h_c . The influence of h_a on performance is more significant. The strategy of collecting solar radiation has a rather weak influence on the dependence of performance on h_a and h_c . As expected, strategy P leads to higher performance (Badescu et al. 2000a).

The maximum output power could be as high as 12 W and 13 W in case of strategies H and P of collecting solar radiation, respectively (Badescu et al. 2000a). This is lower than the designed power of Sojourner PV arrays (16 W at noon).

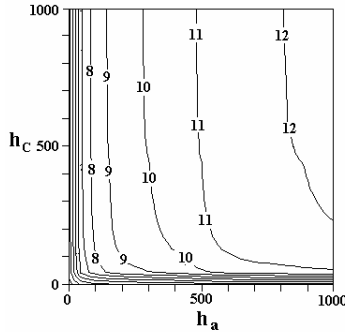


Fig. 5.7 Isolines of maximum power $\dot{W}_{\max}$ provided by the thermal engine as a function of the overall heat transfer coefficients h_a and h_c . Horizontal solar collector (strategy H). Unconcentrated solar radiation was considered (VL1 site, autumn, sol 301, 14.04 LST).

However, this comparison put in disadvantage the solar dynamic system as we used input meteorological data from late autumn at VL1 site while Sojourner was designed to operate during Martian summer. This is a consequence of the fact that none of the 22 complete records available during summer at VL1 site (see Table 2.2 of Chap. 2) corresponds to solar noon.

5.3.2.3 Performance Dependence on Atmospheric Optical Depth

Previous results showed that the dynamic solar power plant performance depends significantly on the heat transfer coefficients h_a and h_c . Practical situations should normally lie between the cases (b) (i.e. medium efficiency engine) and (c) (i.e. high efficiency engine) in Table 5.9. These two cases will be used to provide lower and upper bounds for actual performance. To test the performance of the

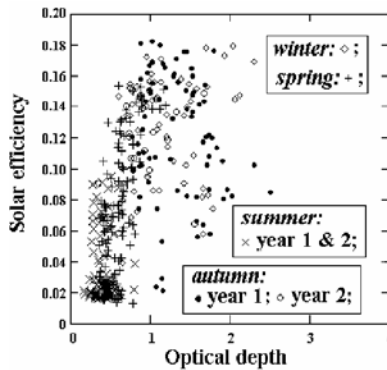


Fig. 5.8 Dependence of solar efficiency $\eta_{\text{solar,opt}}$ on the atmospheric optical depth at VL2 site. High efficiency engine (see Table 5.9) and horizontal solar collector. All the available meteorological data for VL2 site were used.

thermal engine - solar collector combination we simulated its operation at both VL1 and VL2 sites. We analyzed both the horizontal collector (strategy H) and the collector oriented perpendicularly on sun's rays (strategy P), respectively (Badescu et al. 2001a). At VL1 site we used meteorological data from summer, autumn and winter, year 1. All available data were used to simulate the operation at VL2 site. Some results are shown in Fig. 5.8 (for solar energy conversion efficiency) and Fig. 5.9 (for output power).

The influence of latitude on performance is obvious. When the collector is horizontal, the solar energy conversion efficiency is generally smaller at VL1 site as compared to VL2 site (Fig. 5.8). When a P collector is considered, the efficiency increases (at small τ 's) but it still is smaller at VL1 site than at VL2 site (Badescu et al. 2001a). The maximum power provided by a horizontal collector at VL1 site shows some interesting features (Badescu et al. 2001a). Generally, it is smaller than in case of VL2 site. However, there are some situations (for $\tau \approx 1$) when the meteorological effects compensate the latitudinal effects and the output power is quite similar for both VL1 and VL2. If a P collector is used, the power increases for small τ 's but slighter at VL1 site than at VL2 site (Fig. 5.9).

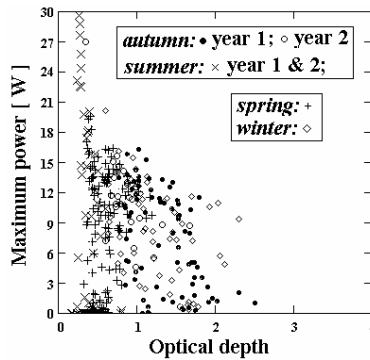


Fig. 5.9 The same as Fig. 5.8 in case of the maximum output power $\dot{W}_{\max}$. High efficiency engine and P solar collector.

In case the medium efficiency engine is coupled to a horizontal collector, the efficiency does not exceed 0.13 at VL2 site (Badescu et al. 2001a). Generally, it is lower during summer, when the horizontal orientation is surely a good option (Badescu 1998a). It is higher during winter, when the optical depth is higher, indicating dust storms occurrence. During dust storms the incident solar radiation is mainly diffuse and the horizontal orientation is the best strategy for radiation collection (Badescu 1998a). In case a medium efficiency engine is coupled to a P collector, the maximum efficiency values lie around 0.13 (Badescu et al. 2001a). The efficiency increases at small optical depth values, which generally correspond to summer. The centre of the output data cloud is placed around 0.09-0.10. The P strategy does not diminish the performance at larger optical depth.

For a horizontal collector attached to a high efficiency engine, the solar efficiency is as high as 0.18 (Fig. 5.8). The qualitative features pointed out previously maintain. The lower sun-to-user efficiency corresponds to lower optical depth. If a P collector is considered, the solar efficiency increases during summer and spring but does not significantly exceed 0.18 (Badescu et al. 2001a). The centre of the output data cloud is placed around 0.15, higher than in case of the horizontal collector. Again, the P strategy does not diminish the performance. This strategy keeps constant the solar efficiency at higher optical depths but improves the performance as compared to the H strategy at smaller optical depths.

The power provided by a system consisting in a horizontal collector and a medium efficiency engine does not exceed 7 W (Badescu et al. 2001a). Generally, it is lower for small optical depth. Indeed, the flux of direct solar energy is higher at smaller optical depth and the horizontal orientation is not recommended in this case. At higher optical depth direct solar radiation diminishes and diffuse radiation increases. As a result, the horizontal orientation is close to optimum. This explains the higher values of $\dot{W}_{\max}$ around $\tau = 1$. For further increase of τ the diffuse radiation flux diminishes. Consequently, $\dot{W}_{\max}$ decreases in this case. If a P collector is considered, the solar efficiency is higher during summer and spring, when the optical depth is small (Badescu et al. 2001a). Generally, the efficiency increases as compared to the H strategy. At high optical depth the solar efficiency is comparable for both H and P strategies.

Using a better engine with a horizontal collector leads to output power up to 13 W for τ around 1 (during sols of spring, autumn and winter) (Badescu et al. 2001a). For small values of τ the output power is smaller. The P strategy is recommended in combination with high efficiency engines (Fig. 5.9). In this case the sun-to-user efficiency during sols with small optical depth increases strongly, exceeding 25 W. The centre of the output data cloud is placed around 13 W. The P strategy can be used at high optical depth, too.

5.3.2.4 Performance Dependence on the Level of Solar Irradiance

The dependence of solar efficiency on the level of incident global irradiance was studied in (Badescu et al. 2001a). In case of a horizontal collector operating at VL2 site, a slightly non-linear relationship exists between solar efficiency and incident global irradiance for both the medium and the high efficiency engines. When the P collector is considered, the dependence is more complicated.

When a combination medium efficiency engine - horizontal collector is considered, the efficiency is higher (whatever the incident irradiance is) during autumn and winter and lower during summer. This rather surprising fact is valid for the P collector, too. It is probably due to the influence of the ambient temperature, which is lower during autumn and winter. The situation is different in case of the high efficiency engine. Then, the solar efficiency is higher during summer, even if it corresponds to lower incident irradiance. This remark is even more obvious when a P collector is considered. A more uniform solar efficiency values distribution is obtained in this case.

In case of a horizontal collector, the efficiency increases by increasing the irradiance level, whatever the type of engine is. For the P collector, the efficiency depends on the irradiance level in a more interesting manner. Thus, the lower bound of the efficiency increases with the irradiance level, but the upper bound practically does not depend on the irradiance level. This is valid for both the medium and high efficiency engines.

During autumn and winter the dependence of η_{solar} on the level of incident global irradiance is nearly similar for both the horizontal and the P collector operating at VL1 site. Important differences exist during summer. The P collector is more effective, as expected. The influence of irradiance level on solar efficiency decreases drastically beyond a certain threshold value (about 300 W/m^2). This applies to both types of solar collectors.

Figure 5.10 shows some results for the output power at VL1 site. Meteorological data from year 1 were used. In case of a horizontal collector the dependence of the maximum output power on the level of global irradiance is not differentiated upon season (Badescu et al. 2001a). When a P collector is considered, the same incident irradiance value leads to an output power obviously higher during summer. For a horizontal collector the output power increases when the input irradiance increases (Badescu et al. 2001a). This remark maintains for the P collector except for summer results (Fig. 5.10).

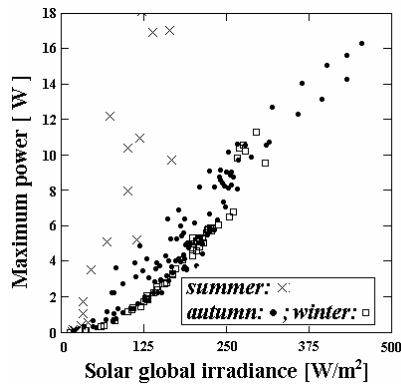


Fig. 5.10 Dependence of maximum output power $\dot{W}_{\text{max}}$ on global irradiance at VL1 site. High efficiency engine (see Table 5.9) and P solar collector. Meteorological data for summer, autumn and winter year 1 were used.

The power provided by a system based on a horizontal collector increases at VL2 site with the level of solar irradiance, as expected (Badescu et al. 2001a). The increase is almost proportional in case of the medium efficiency engine and slightly non-linear for the high efficiency engine. Generally, there is no obvious dependence on season. In case of the P collector, the output power obviously depends on season, with a maximum during spring and summer and a minimum during autumn and winter. This is true for both the medium and high efficiency engines (Fig. 5.11).

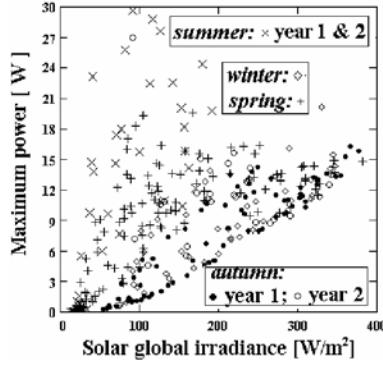


Fig. 5.11 Dependence of the maximum output power $\dot{W}_{\max}$ on the level of solar global irradiance incident on a horizontal surface at VL2 site. High efficiency engine (see Table 5.9) and P solar collector. All the available meteorological data for VL2 site were used.

The seasonal influence is similar for both solar energy conversion efficiency and output power in case of a medium efficiency engine - horizontal collector combination (Badescu et al. 2001a). This is still valid when the collector is connected to a high efficiency engine. However, in this case the power values have a larger dispersion, which increases slightly with increasing the irradiance.

In case of a medium efficiency engine and a P collector, the influence of the season is stronger on power than on solar efficiency (Badescu et al. 2001a). This is even more obvious if one connects a P collector to a high efficiency engine. The high solar efficiency values during spring and autumn at smaller irradiance values are not the main cause of the higher output power (which is obtained in summer (Fig. 5.11)). For a medium efficiency engine, a P collector is recommended mainly during summer and spring (which are dust storm - free seasons) (Badescu et al. 2001a). One finds higher output power values as compared to the case when a horizontal collector is used. If the summer and spring values would be neglected, one can see that choosing a P instead of an H collector leads to a relatively small increase in power during the other two seasons (autumn and winter). This is valid for the high efficiency engine, too (Fig. 5.11). However, the increase in power by using a P collector during seasons without dust storms is more spectacular. Compare the power values as high as 20 W obtained at lower input irradiance by using a P collector (Fig. 5.11) with the power values of at most 12-13 W obtained at high irradiance values by using a horizontal collector (Badescu et al. 2001a).

5.3.2.5 Diurnal Variation of Performances

The input data file contains only a few sols with complete records covering appropriately the whole daylight time. The most part of the sols has one to three records only associated to time periods close to sunrise, noon or sunset. In particular, no summer sol with complete records covering the whole day was found either for VL1 or for the VL2 site. For each season, we selected those sols that are richer in

available data. In case of VL1 these sols are 301 (autumn) and 328 (winter). Note that no available data refers to spring (see Table 2.2 of Chap. 2). In case of VL2 the sols selected are 420 (spring) and 872 (autumn). The sol 406 (winter) is also available but no reference to it will be made here, as the winter conditions are relatively similar for both Viking Lander sites.

Various efficiencies defined in Section 5.1.3 were reported in Badescu et al. (2000b) in case of sol 301 (Martian autumn) at VL1 site. During most of the time the optimum engine efficiency $\eta_{\text{engine,opt}}$ lies around 33 %. The efficiency is decreasing suddenly near sunset. Generally, the optimum engine efficiency is less dependent on the type of engine and on the strategy of collecting solar radiation. In exchange, the system efficiency $\eta_{\text{system,opt}}$ is strongly dependent on engine quality and less dependent on the strategy of solar collection. It lies around 0.2 for the high efficiency engine and around 0.15 for the medium efficiency engine. When the high efficiency engine is considered, the decrease in performance is more abrupt near sunset.

The optimum solar efficiency $\eta_{\text{solar,opt}}$ is smaller than the optimum system efficiency (Fig. 5.12) but exhibits the same qualitative features. Generally, it doesn't exceed 0.15 for the high efficiency engine and 0.10 for the medium efficiency engine. The strategy of collecting solar radiation has not a strong influence on $\eta_{\text{solar,opt}}$. In exchange, the strategy significantly influences the maximum output power $\dot{W}_{\text{max}}$ (Fig. 5.13). If the optimum solar efficiency is almost constant during the day, the maximum power's time variation is closely related to the temporal variation of solar irradiance. This is more obvious for the high efficiency engine. The maximum output power can exceed 15 W for the high efficiency engine and doesn't exceed 8 W for the medium efficiency engine. This proves that properly designed thermal power plants are comparable in performance with PV-based power systems (one reminds that Sojourner's design output power is 16 W at solar noon). Moreover, the previous analysis puts in disadvantage the solar dynamic

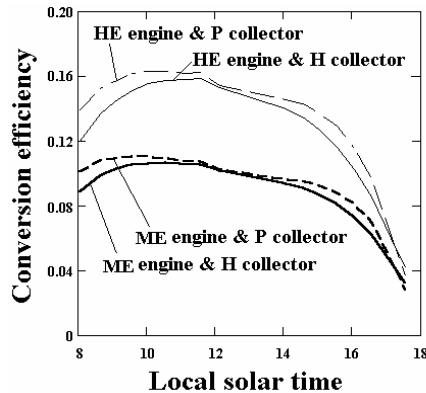


Fig. 5.12 Optimum solar efficiency $\eta_{\text{solar,opt}}$ during sol 301 (autumn) at VL1 site. Medium efficiency engine (ME) and high efficiency engine (HE) (see Table 5.9). Strategy H - horizontal collector; Strategy P - collector permanently kept perpendicular on Sun's rays.

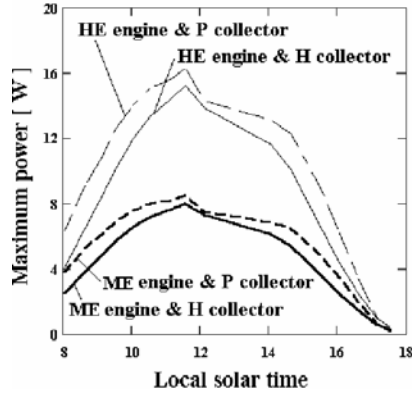


Fig. 5.13 The maximum output power $\dot{W}_{\max}$ during sol 301 (autumn) at VL1 site. For details see Fig. 5.12.

system as we used here input meteorological data from late autumn at VL1 site while Sojourner was designed to operate during Martian summer.

The hourly variation of solar collector's optimum temperature is shown in Fig. 5.14. It is less dependent on the strategy of collecting solar radiation and a little more dependent on engine quality. The high efficiency engine leads to a smaller optimum collector temperature. Generally, the collector temperature exceeds with more than 100 K the ambient temperature. The hourly variation of $T_{C,\text{opt}}$ is stronger than that of the ambient temperature. This proves that $T_{C,\text{opt}}$ is mainly controlled by the level of incident solar radiation.

The optimum temperature of the working fluid in the cold part of the engine (T_{opt}) is well correlated with the time variation of the ambient temperature (Badescu et al. 2000b). T_{opt} is smaller in case of the high efficiency engine, when the influence of the strategy of collecting solar radiation is obvious. This influence is less

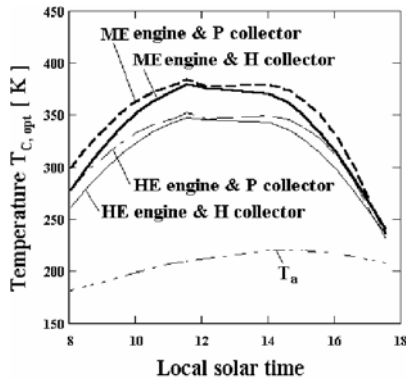


Fig. 5.14 Optimum solar collector temperature $T_{C,\text{opt}}$ associated to solar thermal power plant operation during sol 301 (autumn) at VL1 site. For details concerning the power plant see Fig. 5.12.

important in case of the medium efficiency engine. In exchange, the optimum temperature of the working fluid in the worm part of the engine (T''_{opt}) is better correlated with the hourly variation of the solar radiation (Badescu et al. 2000b). Both the engine quality and the strategy of collecting solar radiation are important factors. Generally, T''_{opt} is close to $T_{\text{C,opt}}$.

Sol 328 belongs to winter at VL1 site. The main performance indicators of the solar thermal power plant are studied in Badescu et al. (2000b). The optimum solar efficiency values are rather close to the autumn values. The quality of the engine is very important and the strategy of collecting solar radiation is less important, as far as their influence on the performance indicators is considered. This is due to the fact that sol 328 belongs to a dust storm period (Badescu 1998a). The maximum output power is, however, much smaller than during autumn. At noon it reaches 10 W in case of the high efficiency thermal engine but doesn't exceed 5 W in case of the medium efficiency engine. The maximum output power time variation is stronger than that of solar efficiency but this is less obvious than in autumn. The daily variation of the optimum collector temperature is rather weak. Generally, the high efficiency engine leads to a lower optimum collector temperature. Also, the optimum temperature is lower for a collector perpendicular on Sun's rays.

Sol 420 belongs to springtime at VL2 site. In this case, the optimum solar efficiency depends significantly both on engine quality and on the strategy of collecting solar radiation (Badescu et al. 2000b). In case of a P collector, the optimum solar efficiency is nearly constant during the day. It varies rather much for the horizontal collector (with a maximum at noon). The optimum solar efficiency values are quite close to those from autumn and summer at VL1 site. The maximum output power shows features similar to those of the optimum solar efficiency. Generally, the P collector assures a more constant maximum output power during the day. The engine quality is very important. The high efficiency engine connected to a P collector can ensure a maximum output power around 15 W during most part of the day. This is close to the design power of the PV system of Mars Pathfinder's Sojourner. When a P solar collector is considered, the optimum collector temperature shows a remarkable constancy during the day.

Sol 872 corresponds to autumn at VL2 site. The optimum solar efficiency shows an interesting variation during the day. This is more obvious for a P collector (Badescu et al. 2000b). In case of the horizontal collector, the optimum solar efficiency has a maximum around the noon. The optimum solar efficiency is higher in case of the high efficiency engine, as expected. It ranges from 8 to 16 %. The maximum output power shows similar features. Generally, the better performance in the morning corresponds to the stronger solar irradiance during that part of day (Badescu 1998a). Note that a horizontal collector assures a constant power during the day. The high efficiency engine should be used in combination with a P collector. A maximum output power of 15 W can be provided only a short time period during the day. In case of a P collector, the optimum temperature is rather constant until 14.00 LST. When a horizontal collector is considered, the optimum temperature has a maximum reached between 12.00 and 14.00 LST. Generally, $T_{\text{C,opt}}$ is lower than in the cases above and this can be correlated to the smaller ambient temperature value.

5.3.2.6 Correlation between Power and Conversion Efficiency

The dependence of the maximum output power on the optimum solar efficiency at VL1 site is shown in Badescu et al. (2000b). Meteorological data from year 1 were used there. Let us consider the case of the medium efficiency engine. The maximum output power increases when the optimum solar efficiency increases, as expected. There is little dependence on season, except for a few summer values in case of the P collector, when the solar efficiency is obviously higher. Broadly speaking, there is little difference between the maximum output power provided by systems based on H and P collectors, respectively. The highest optimum solar efficiency is 0.11 and the maximum output power doesn't exceed 10 W. When the high efficiency engine is considered, the influence of optimum solar efficiency on the maximum output power is important. The highest optimum solar efficiency is 0.16 and the output power can be as high as 15 W for an H collector and 17 W for a P solar collector.

Figure 5.15 shows some results obtained at VL2 site (Badescu et al. 2000b). All the available meteorological data for the two years of VL2 operation were used in computations. Generally, the dependence of the maximum output power on the optimum solar efficiency is non-linear. In case of a horizontal collector, the dependence seems to indicate a quadratic dependence ($\dot{W}_{\max} \propto \eta_{\text{solar,opt}}^2$). The coefficient of proportionality is smaller in case of the medium efficiency engine (Badescu et al. 2000b). When the P collector is considered, the dependence $\dot{W}_{\max}(\eta_{\text{solar,opt}})$ is more complicate, but keeps the quadratic feature. The P collector has a more compact dispersion of the optimum solar efficiency values. It ranges from 8 to 12 % in case of the medium efficiency engine and between 13 and 19 % in case of the high efficiency engine.

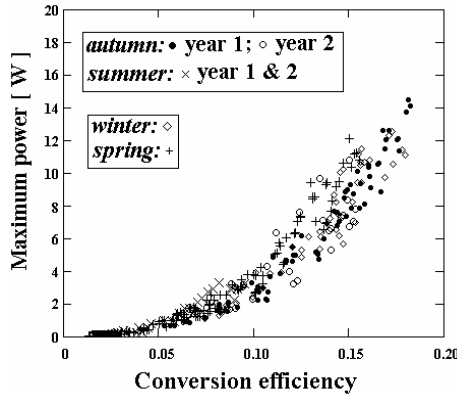


Fig. 5.15 Dependence of the maximum output power $\dot{W}_{\max}$ on the optimum solar efficiency $\eta_{\text{solar,opt}}$ at VL2 site. High efficiency engine (see Table 5.9) and horizontal solar collector. Meteorological data for summer, autumn and winter (year 1) and spring, summer and autumn (year 2) were used.

In all cases a certain optimum solar efficiency threshold (around 5 %) must be exceeded in order the system provide useful power. The dependence of the maximum output power on optimum solar efficiency is stronger in case of the high efficiency thermal engine than in case of the medium efficiency engine, on one hand, and in case of the P collector than for the horizontal collector, on the other one hand. It seems no obvious difference exists between the performances of the power plant in the two years of VL2 operation.

5.4 Solar Stirling Power Engine

A more realistic solar thermal engine is considered in this section. It consists of a solar collector - Stirling engine combination. The Stirling engine is indeed very attractive due to its operation at low temperature difference between the two heat reservoirs. This could enable power production during the Martian dust storm period, when both the incoming solar energy flux and collector temperature are small. Preliminary results were briefly reported in Badescu et al. (2001b) where the diurnal solar plant operation is studied. One concluded that the efficiency of a usual (Earth based designed) Stirling solar engine diminishes with about 8 % when operates under Martian weather conditions. However, the recommended volumetric ratio lies between 1 and 2.6 and the best thermal agent is helium, in agreement with conclusions based on Earth made experiments. The model previously proposed in Badescu et al. (2001b) is now presented. A number of improvements are also included (Badescu 2004).

5.4.1 Solar Engine Model

The solar engine consists of a selective flat-plate solar collector coupled to a Stirling engine with partial heat regeneration. No heat storage system is considered in this approach.

5.4.1.1 Solar Collector Model

First, we shall consider the flat-plate solar collector (Fig. 5.16). Its main components are the collector plate and a transparent cover of thickness a . The gap of thickness s between these two components is filled with carbon dioxide at Martian atmospheric pressure. Solar direct and diffuse radiation penetrates the transparent cover and is absorbed by the collector plate. The thermal energy generated in the solar collector plate is transferred to the thermal agent at the hot head of the Stirling engine and later-on part of it is converted into work.

Steady state energy balance for the solar collector yields

$$\dot{Q}_{abs} - \dot{Q}' - \dot{Q}_{lost} = 0. \quad (5.54)$$

Here $\dot{Q}_{abs}$ is the thermal energy flux generated into solar collector plate, $\dot{Q}_{lost}$ is the heat flux lost towards the ambient and $\dot{Q}'$ is the heat flux transferred to the

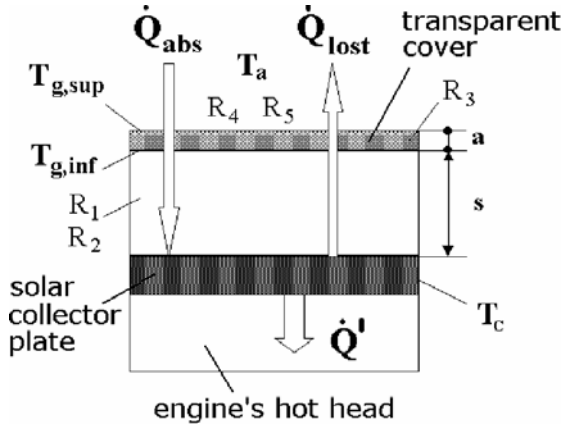


Fig. 5.16 The solar collector of the Stirling engine

thermal fluid inside the Stirling engine. The thermal energy flux generated into the solar collector plate is given by

$$\dot{Q}_{abs} = \varphi_{abs} A_C, \quad (5.55)$$

where A_C is the area of collector plate surface. The heat flux lost towards the ambient is given by the usual Newton relationship:

$$\dot{Q}_{lost} = U_L A_C (T_C - T_a), \quad (5.56)$$

where U_L is the overall heat loss coefficient, while T_C and T_a are collector and ambient temperature, respectively. Note that T_C is an averaged value over collector surface and normally is not constant in time.

Seven temperatures are associated to solar collector operation (Badescu 2004). With a single except (i.e. the average temperature of bottom insulation) they have the meaning explained in Tables 5.2 and 5.3. The collector heat losses could be studied by using the thermal resistance method. Then, the flux of heat losses $\dot{q}_{lost}$ per unit collector surface area is defined by:

$$\dot{q}_{lost} \equiv \frac{\dot{Q}_{lost}}{A_c} = U_L (T_C - T_a) = \frac{T_C - T_a}{R_{tot}}, \quad (5.57)$$

where R_{tot} is the total thermal resistance given by

$$R_{tot} = \frac{R_1 R_2}{R_1 + R_2} + R_3 + \frac{R_4 R_5}{R_4 + R_5} \quad (5.58)$$

Note that R_{tot} here is equivalent to R_{1-5} in the model of solar collector of section 5.1.1. Therefore, Fig. 5.2 and Table 5.3 show the meaning of the thermal resistances R_1 to R_5 . Details concerning the computation of these thermal resistances are similar to those presented in Section 5.1.1 and will be not repeated here.

5.4.1.2 Stirling Engine Model

During the 1980s research was started on low temperature differential Stirling engines. A first Stirling engine running with a temperature difference below 20 degrees Celsius has been developed (Senft 1996). Meanwhile a rather large number of research or commercial Stirling engines using unconcentrated solar radiation were built, with powers from a few to tens of Watt (Badescu 2004).

A simple Stirling engine model is used at this stage of the analysis. It was first developed in Howell and Bannerot (1977) and slightly improved in Badescu (1992). The model is based on two simplifying assumptions. First, one neglects the heat losses during the thermal transfer from the solar collector to the working fluid inside the engine. Second, one neglects the friction of the moving parts. These make of course the results reported below to be upper bounds for the performance of a real solar Stirling system. The Stirling cycle efficiency $\eta_{Stirling}$ is defined as:

$$\eta_{Stirling} = \frac{P}{\dot{Q}'} = \frac{\eta_{max}}{1 + D\eta_{max}}, \quad (5.59)$$

where P is the output mechanical power while $\eta_{max} = 1 - T_a / T_C$ is the maximum efficiency of the cycle in case of perfect heat regeneration. In case the thermal agent is an ideal gas the parameter D is given by Howell and Bannerot (1977), Badescu (1992):

$$D = \frac{x}{(k-1) \ln \varepsilon_V}. \quad (5.60)$$

Here $x (\in [0,1])$ is the heat regeneration factor, k is the adiabatic exponent of the thermal agent and ε_V is the volumic ratio (i.e. the ratio of the extreme values of the thermal agent total volume). $x = 0$ means ideal heat regeneration. In this case the efficiency of the Stirling engine Eq. (5.59) equals the Carnot efficiency.

Use of Eqs. (5.54), (5.55), (5.56) and (5.59) yields the following dependence of the power provided P on the collector plate temperature T_C :

$$P(T_C) = \frac{1 - T_a / T_C}{1 + D(1 - T_a / T_C)} [\varphi_{abs} - U_L(T_C - T_c)] A_C. \quad (5.61)$$

Note that U_L is not a constant but depends on T_C (among other variables) (see Fig. 5.17). Consequently, a simple numerical procedure to maximize directly the power P given by Eq. (5.61) was used here, as follows. One monotonously increases the plate temperature T_C starting from the ambient temperature. For any value of T_C one evaluates first the overall heat loss coefficient U_L (Eq. (5.57)) and then the output power P (Eq. (5.61)). The maximum power P_{max} and the appropriate optimum plate temperature $T_{C,opt}$ are finally selected from the series of results.

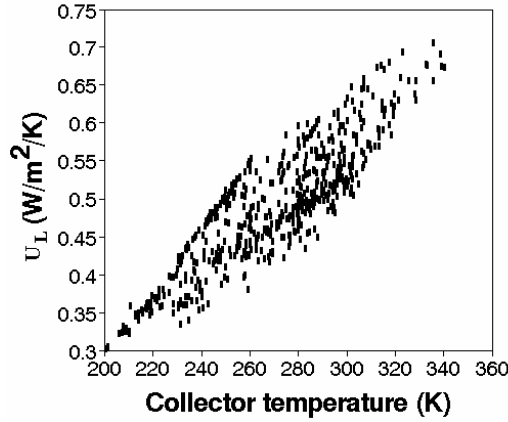


Fig. 5.17 Dependence of overall heat loss coefficient U_L on collector temperature. All available meteorological data were used (see Table 2.2 of Chap. 2).

Figure 5.17 shows that the overall heat loss coefficient U_L increases by increasing the collector temperature. The values of U_L range between 0.3 and 0.7 $\text{Wm}^{-2}\text{K}^{-1}$. Broadly, these values are smaller than those of Earth located flat-plate vacuum solar collectors (see e.g. Benz and Beikircher (1999) where the experimentally derived overall heat loss coefficient is about 1.25 $\text{Wm}^{-2}\text{K}^{-1}$ during a rather heavy utilization as steam production). They are slightly smaller than the results obtained during simulation of the Carnot solar engine in section 5.3 (U_L values between 0.5 and 1 $\text{Wm}^{-2}\text{K}^{-1}$). This is to be expected as an (ideal) Carnot engine normally operates at higher collector temperature than the Stirling engine considered here. The dependence of U_L on collector temperature justifies a posteriori the numerical optimization procedure we used in this section.

The way of using the output power of the Stirling engine is not relevant for this study as the key aspect here is the comparison with the output power of a similarly sized PV-based system. Consequently, electric generators and/or gear boxes are not considered, neither efficiencies for these (possible) components are included in the model.

Use of the output power P allows to define the solar energy conversion efficiency (or solar-to-user efficiency) as $\eta \equiv P/(\varphi_{\text{inc}} A_C)$. The maximum solar efficiency is given by

$$\eta_{\text{sol,max}} = P_{\text{max}} / (\varphi_{\text{inc}} A_C). \quad (5.62)$$

Note that in the case analysed here both η_{sol} and P have their maximum for the same value $T_{C,\text{opt}}$.

5.4.2 Results and Discussions

A horizontal solar collector is considered. This is the easiest-to-use strategy. It gives for many periods of time a performance less than 10 % smaller than the

strategies involving more sophisticated, orientable, solar collectors (Badescu et al. 2000a, 2000b, 2001a). Details about solar collector design are given in Table 5.8 (where the information about the bottom insulation should be omitted of course). The values of the effective transmittance-absorptance products were computed with $(\tau\alpha)_{\text{dir}} = (\tau\alpha)_{\text{dir}} = \tau\alpha$.

Three Stirling engine thermal agents are usually considered: carbon dioxide (adiabatic exponent $k = 1.33$), air ($k = 1.4$) and helium ($k = 1.66$). Helium gives the best performance and is our choice for this section. A simple analysis proves that the Stirling engine efficiency increases by increasing the compression ratio ε_V . Here the value $\varepsilon_V = 2$ is adopted as a good compromise between better performance and smaller engine size. Increasing the heat regeneration parameter x from the ideal value $x = 0$ diminishes the engine output power. Here the value $x = 0.2$ is accepted, in agreement with current terrestrial practice.

Results of computations performed by using the meteorological data during the autumn and winter of the first year at VL1 site are shown in Fig. 5.18. It is obvious that both the maximum power P_{max} and the maximum solar efficiency $\eta_{\text{sol,max}}$ increase around the solar noon. However, $\eta_{\text{sol,max}}$ seems to be less dependent on solar time than P_{max} . The maximum power of the solar Stirling engine around the noon is comparable in magnitude with the designed power of Sojourner's PV cells system (i.e. 16 W). Also, the solar efficiency is as large as 18 %, which is close to the design value of Sojourner's PV cells efficiency (about 18 %). Note, however, that the horizontally placed collector is a good solar energy collection strategy especially during autumn and winter. Indeed, results not shown here prove that during spring and summer the solar Stirling engine performance is slightly worse. During the warm season other strategies of collecting solar energy are much more effective (Badescu 1998a).

The large dispersion of the results in Fig. 5.18 is mainly due to the influence of optical depth. The performances of solar Stirling engine obviously decrease by

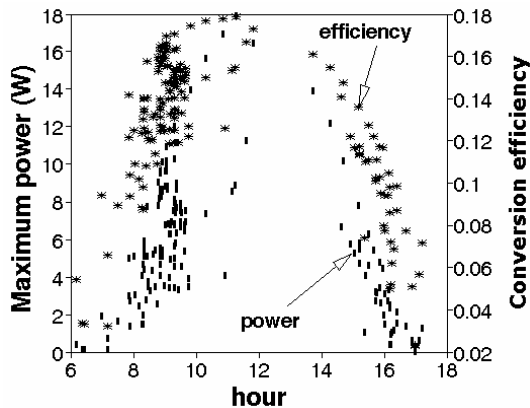


Fig. 5.18 Dependence of maximum power P_{max} and maximum solar efficiency $\eta_{\text{sol,max}}$ on local solar time (in Earth hours). Results obtained by using the meteorological data during the autumn and winter in the first year at VL1 site.

increasing the atmospheric optical depth (Badescu 2004). The maximum efficiency $\eta_{sol,max}$ is less dependent on the optical depth than the maximum power P_{max} . Note that under-unitary optical depth values are usually associated with “clear sky” conditions while during the dust storm the optical depth has larger values (Badescu 2001).

The dependence of the maximum output power P_{max} on optimum solar efficiency $\eta_{sol,max}$ is shown in Fig. 5.19. All the meteorological data of Table 2.2 in Chap. 2 were used. The maximum output power increases when the optimum solar efficiency increases. Generally, the dependence of P_{max} on $\eta_{sol,max}$ seems to indicate a quadratic relationship. This is in agreement with previous results obtained in case of solar Carnot engines.

A certain optimum solar efficiency threshold (around 5 %) must be exceeded in order the system provide useful power. Again, this confirms previous results reported in section 5.3. The optimum solar collector temperature $T_{C,opt}$ increases by increasing the solar efficiency, as expected. The larger dispersion of the $T_{C,opt}$ values for the same value of the solar efficiency is mainly due to the difference in the solar time.

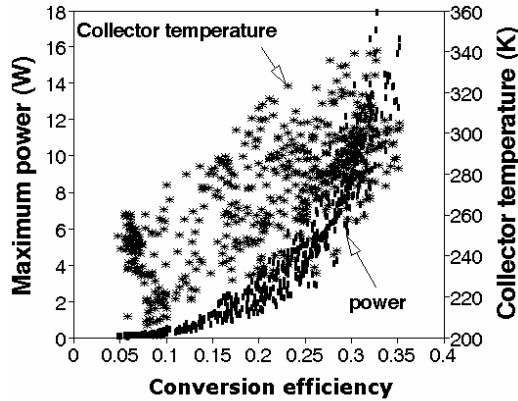


Fig. 5.19 Dependence of the maximum power P_{max} and optimum collector temperature $T_{C,opt}$ on maximum solar efficiency $\eta_{sol,max}$. All available meteorological data were used (see Table 2.2 of Chap. 2).

5.5 Conclusions

The chapter focuses on solar thermal power generation on Mars surface. A “dynamic” solar power plant (which consists in a solar collector - thermal engine combination) is proposed as an alternative for the more usual photovoltaic cells.

Upper bounds for the efficiency of solar thermal power plants operating in the Martian environment are evaluated in section 5.2. The earlier theories predict too high efficiencies for radiation energy conversion into work to be of practical interest. Much more accurate simple upper bounds were already proposed in literature. For reader convenience they are summarized in section 5.2 and applied to power plants

operating on Mars under both direct and diffuse solar illumination. Both black-body and selective absorbers were considered.

A more elaborated but still idealized model uses a Carnot cycle to describe solar engine operation in section 5.3. The solar power plant is designed to operate during the whole Martian year. Consequently, it contains a *selective* flat - plate solar collector. A detailed model of collector heat losses towards the ambient is developed. The optimization procedure developed in section 5.3.1 is based of finite-time thermodynamics methods. The following two strategies of collecting solar energy were analysed: (i) horizontal collector - strategy H; (ii) the collector tilt and orientation are continuously adjusted to keep the receiving surface perpendicular on Sun's rays - strategy P. The first strategy is easier to implement and use in practice while the later strategy provides higher collected solar energy most time of the year. A medium and a high efficiency thermal engine were analysed. Practical situations should normally lye between these two cases. All the computations were performed for a solar collector comparable in size with Pathfinder's Sojourner (solar energy collection area of 0.22 m^2). During the application we used as input data values of atmospheric pressure and temperature, wind speed and atmospheric optical depth measured at Viking Landers sites. The main results are:

(1) The heat losses between the solar collector absorber plate and transparent cover are exclusively by conduction. This differs from the Earth-based solar collector where the main heat loss mechanism is convection.

(2) The convection heat transfer above the transparent cover is laminar. This differs from the Earth-based solar collectors where turbulence is the main convection mechanism.

(3) For the design solution we selected, the values of the overall heat loss coefficient U_L range between about 0.5 and $1 \text{ Wm}^{-2}\text{K}^{-1}$. Roughly, these values are comparable with those of Earth located vacuum solar collectors. The dispersion of the U_L values is slightly smaller during winter and higher during autumn. No obvious dependence of U_L on the optical depth is observed. However, the dispersion of the U_L values is larger for values during the "clear" days. U_L does not depend significantly on the latitude of the solar collector.

(4) Two parameters are used to quantify the heat transfer inside the thermal engine. They are h_a (the heat transfer coefficient between the working fluid passing through the radiator of the heat engine and ambient; see Eq. (5.40)) and h_c (the heat transfer coefficient between solar collector and working fluid (see Eq. (5.37)). The influence of h_a on performance is more significant.

(5) The strategy of collecting solar radiation has a rather weak influence on the dependence of performances on h_a and h_c . As expected, strategy P leads to higher performances.

(6) The dynamic solar power plants equipped with selective flat - plate collectors could provide power comparable to that of similar-size PV cell systems.

(7) The influence of latitude on performance is obvious. Generally, the solar efficiency is smaller at VL1 site as compared to VL2 site for both strategies of collecting solar radiation. In most cases the maximum power provided by a horizontal collector at VL1 site is smaller than at VL2 site. However, in some

situations the meteorological effects compensate the latitudinal effects and the output power is quite similar at both VL1 and VL2 sites.

(8) In case a medium efficiency engine is coupled to a horizontal collector, the solar efficiency does not exceed 0.13 at VL2 site. Generally, it is lower during summer and higher during winter's dust storms. In case the medium efficiency engine is coupled to a P collector, the solar efficiency increases during summer.

(9) The solar efficiency is as high as 0.18 in case of a horizontal collector attached to a high efficiency engine. If the high efficiency thermal engine is connected to a P collector the solar efficiency increases significantly during summer and spring but does not exceed 0.18.

(10) Using a high efficiency engine coupled to a horizontal collector leads to output power up to 13 W during spring, autumn and winter.

(11) The P strategy is recommended mainly during summer and spring in combination with high efficiency engines. In this case the output power could be as high as 25 W.

(12) During an autumn day at VL1 site (sol 301) the optimum engine efficiency is around 33 %. The system efficiency lies around 20 % for the high efficiency engine and around 15 % for the medium efficiency engine. The optimum solar efficiency doesn't exceed 15 % and 10 %, respectively, in the two cases. The maximum output power can exceed 15 W and doesn't exceed 8 W for the high and medium efficiency engine, respectively.

(13) During a winter dust-storm day at VL1 site (sol 328) the maximum output power is much smaller than during autumn. At noon it reaches 10 W in case of the high efficiency thermal engine but doesn't exceed 5 W in case of the medium efficiency engine.

(14) During a spring day at VL2 site (sol 420) the optimum solar efficiency values are quite close to those from autumn and summer. The high efficiency engine connected to a solar collector kept perpendicular on Sun's rays can ensure a maximum output power around 15 W during most part of the day. This is close to the design power of the PV system of Mars Pathfinder's Sojourner.

(15) During an autumn day at VL2 site (sol 872) the optimum solar efficiency ranges from 8 to 16 % in case of a good quality engine. The high efficiency thermal engine should be used in combination with a solar collector kept perpendicular on Sun's rays. A maximum output power of 15 W might be provided a short time period during the day.

(16) When a horizontal solar collector is considered, the dependence of the maximum output power on optimum solar efficiency seems to be quadratic at both VL1 and VL2 sites. When a collector perpendicular on Sun's rays is considered, this dependence is more complicate, but keeps the quadratic feature.

(17) A certain optimum solar efficiency threshold (around 5 %) must be exceeded in order the system provide useful power.

(18) The dependence of the maximum output power on the optimum solar efficiency is stronger in case of a high efficiency thermal engine than in case of a medium efficiency engine, on one hand, and in case of a collector kept perpendicular on Sun's rays than in case of a horizontal collector, on the other one hand.

(19) No obvious difference exists between power plant performances in the two years of VL2 operation.

A solar Stirling engine based on a horizontal selective flat-plate converter was analyzed in section 5.4. A numerical optimization procedure was used to maximize the power provided by the engine. The main results are as follows:

(1) The values of the overall heat loss coefficient U_L range between about 0.3 and $0.7 \text{ W m}^{-2} \text{ K}^{-1}$.

(2) The solar energy conversion efficiency at noon could be as high as 0.18 at VL2 site during autumn and winter. Generally, it is lower during spring and summer.

(3) The output power at noon produced by the Stirling engine at VL2 site was as high as 16 W during autumn and winter. It obviously decreases during the dust storm periods.

(4) Properly designed solar Stirling engines equipped with horizontal flat-plate collectors could provide output power comparable in magnitude to that of PV cell systems. However, this conclusion should be treated with caution as it is based on figures referring to an existing PV system, on one hand, and to a simplified solar Stirling engine model, on the other one hand.

(5) To increase the output power and the efficiency, the design parameters of Stirling engines operating on Mars should be different from those of terrestrial engines. For example, one expects the compression ratio to exceed the usual value $\varepsilon_v=2$ while a smaller regeneration factor than $\chi = 0.2$ to be implemented.

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